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Novel Phase Modulator for ELA-Based Lateral Growth of Si

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Phase-modulated excimer laser annealing (ELA) is an advanced excimer-laser crystallization method characterized by the intensity modulation of irradiated light by a phase modulator. In this method, a temperature gradient is formed in melted Si and large crystal grains are laterally grown at predetermined positions. In order to form grains with a high packing efficiency, a periodic "V-shaped" form of the light intensity distribution is desired. In the present study, a novel duty phase modulator is developed for projection-type PMELA. The light intensity distribution on the sample surface can be freely controlled and its design method is simple. We confirmed that a V-shaped light intensity distribution could be achieved by preparing a prototype duty phase modulator. In addition, crystallization was carried out with this duty phase modulator and 5-μm-long crystal grains with a high packing efficiency were successfully grown.
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Excimer laser crystallization (ELC) is a key technology for polycrystalline Si thin-film transistors (poly-Si TFTs) designed for system-on-glass devices and has been the subject of numerous studies. Phase-modulated excimer laser annealing (PMELA), which we have been investigating, is an advanced ELC method featuring the intensity modulation of irradiated light on a-Si using a phase modulator (Fig. 1). In this method, a temperature gradient is formed in melted Si and large crystal grains grow laterally at predetermined positions. In this way, a TFT channel section can be prepared from a single-crystal grain. TFTs of higher performance can be prepared from these large crystal grains than from conventional poly-Si.

In order to form a whole circuit, it is necessary to grow large crystal grains with a high packing efficiency. For this purpose, the distribution of the light intensity is determined based on the following characteristics of lateral growth.

1. Lateral growth starts at a certain "lateral growth starting intensity". At a lower light intensity, Si does not melt or it remains in the form of fine grains.
2. Lateral growth takes place along the direction of the temperature gradient, namely, the direction of the light intensity gradient. If this gradient is small, the lateral growth will stop halfway.

Based on these characteristics, we have identified the optimum distribution to have a periodic "V-shaped" form to grow crystal grains with a high packing efficiency. As shown in Fig. 2, crystal nuclei are generated at the bottom of the V-shape irradiating light intensity distribution. Subsequently, lateral growth can take place along the gradient of the V-shape to peak intensity points. In this way, it is possible to grow large crystal grains with a high packing efficiency. It is important that the light intensity at the bottom of the V-shape is exactly the lateral growth starting intensity. If the intensity at the bottom of the V-shape is too low, large grains cannot be formed in those regions. If the intensity at the bottom of the V-shape is too high, random nucleation, resulting in small grains, takes place at the bottom of the V-shape.

In a previous report, 3-μm-long crystal grains were formed using a line-and-space (L&S) type phase modulator.[1] By this method, however, the desired V-shaped light intensity distribution could not be achieved, even when the optical system was carefully adjusted. A concave distribution was obtained, but it was localized and control of the light intensity at the bottom of the distribution was difficult. Therefore, crystallization with a high packing efficiency could not be achieved.

In order to improve this method, a new duty phase modulator was developed.[2] In this report, the principle, design method, and advantages of this duty phase modulator are explained and the results of a crystallization experiment using the duty phase modulator are reported.

Advanced Optical System for PMELA

With reference to Fig. 3, we compare the newly developed method (advanced projection PMELA system) with the conventional method (basic PMELA system). The proximity exposure method and the projection exposure method are used in basic optical systems. An L&S type phase shifter is used in both methods. In the proximity exposure method (a), irradiation is performed keeping a fixed gap between the phase shifter and the substrate. The light intensity distribution is controlled by a Fresnel diffraction pattern generated by the gap. In the projection exposure method (b), an image of the phase shifter is formed by the optical imaging system and the substrate is placed away from the image at a defocused position. Thus, the light intensity distribution is controlled by a Fresnel diffraction pattern generated by the defocusing. The control factors of the light intensity distribution in the proximity exposure method are the illumination conditions of the phase shifter and the width of the gap. In the projection exposure method, the control factors are the illumination conditions of the phase shifter, the defocus value, which corresponds to the gap width, and the numerical aperture (NA) of the optical imaging system. The amplitude point spread function (ASF) of the optical imaging system. The light intensity distribution on the sample surface is more deformed in (b) than in (a), because the NA filters highly diffracted light.

In the advanced PMELA system, the above-mentioned effect of the NA is applied in a constructive manner. The phase shifter is imaged on the sample surface deformed by the ASF. In other words, an optical imaging system is used, but defocus is not used. The light intensity distribution is controlled with a fine concavo–convex plane pattern prepared on the shifter surface. The concavo–convex plane pattern can be freely created, and thus controllability of the light intensity distribution can be drastically improved. As a result, it is possible to create an ideal V-shaped distribution.

A duty phase modulator is a set of fine phase modulation units called "cells." The phase of the background is set at 0° and the phase of the phase modulation area with respect to the phase of the background is designated by θ. The percentage of the phase modulation area on a cell is called the "duty."

For the time being, we assume that the duty is constant, that is, the pattern is perfectly periodic. In addition, the cells are considered to have a one-dimensional arrangement as shown in Fig. 4a. Then, because the duty phase modulator can be considered a kind of dif-

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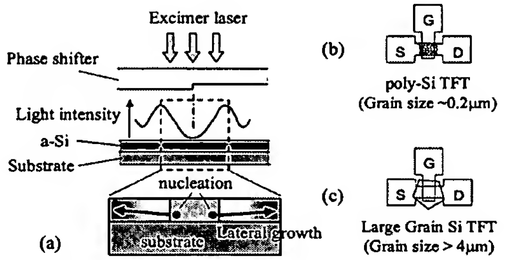

Figure 1. Schematic of PMELA and microstructure in channel area of each TFT: (a) lateral growth in PMELA, (b) conventional poly-Si TFT, and (c) large-grain Si TFT by PMELA.

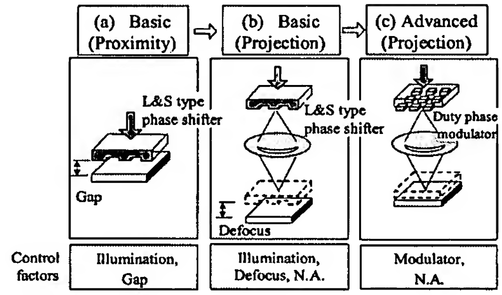

Figure 3. Optical systems for PMELA.

fraction grating, the transmitted light is discretely diffracted and the diffraction angle θ can be expressed by the following equation, based on Fig. 4b

$$\sin \theta_m = m\lambda/p$$

where p is the cell pitch, m is the diffraction order, and λ is the wavelength of laser light.

As shown in Fig. 4c, if p is set to be less than a certain critical value, diffracted light other than 0th order escapes outside the pupil of the optical imaging system. As a result, only the 0th-order light reaches the image plane. An image is formed only by the interference on the image plane of higher order light diffracted from the object. Accordingly, fine patterns do not appear under these conditions and the image takes a uniform intensity distribution. In this case, the normalized light intensity, I, is equal to the light intensity of the 0th-order diffraction and can be expressed by the following equation

$$I = |U|^2 = \left| \frac{1}{p} \int_0^p e^{i\varphi(x)} dx \right|^2 \qquad [1]$$

where U is the complex amplitude of light and $\varphi(x)$ is the phase distribution of the duty phase modulator. Thus, the light intensity can be adjusted by changing $\varphi(x)$, namely, the geometry of the phase modulation area in the cell.

The above concept is true for the case in which cells take a two-dimensional arrangement as shown in Fig. 5. Although the diffraction is two-directional, a similar equation can be derived from Eq. 1 by using two-dimensional integration.

Image formation with optical imaging systems is classified into coherent imaging, in which the image is formed by illumination from a point light source, incoherent imaging, in which the image is formed by illumination from a sufficiently large and perfectly incoherent light source, and partial coherent imaging, which is intermediate between the two. For a partial coherent imaging, in which a real optical system is applied to, the light intensity distribution can be obtained from the equation derived by Hopkins.[3] However, it seems difficult to derive a simple expression from this equation for this case. Therefore, we consider here the case of an approximation to coherent imaging.

The amplitude distribution $U(x,y)$ on the image plane by coherent imaging can be obtained from Fourier imaging theory by the convolution shown in Eq. 2[4]

$$U(x,y) = \int\int T(\xi,\eta) ASF(x - \xi, y - \eta) d\xi d\eta \qquad [2]$$

where $T(x,y)$ is the complex amplitude transmittance of the object (duty phase modulator) and $ASF(\xi,\eta)$ is the amplitude point spread function (complex amplitude distribution formed by a point object) of an optical imaging system.

The ASF can be obtained by the Fourier transformation of the pupil function of the optical imaging system. $ASF(\xi,\eta)$ can be expressed by the following equation

$$ASF(\xi,\eta) = \frac{2J_1(2\pi\ NA\ r/\lambda)}{2\pi\ NA\ r/\lambda} \qquad [3]$$

$$r = \sqrt{\xi^2 + \eta^2}$$

where λ is the wavelength of the light, NA is the numerical aperture of the optical imaging system, and J_1 is the first-order Bessel function.

Because it is difficult to evaluate Eq. 2 using Eq. 3 in this form, Eq. 3 is approximated by a cylindrical function of radius R as shown in Fig. 6. That is

$$ASF(\xi,\eta) = \begin{cases} 1 & r \leq R \\ 0 & r > R \end{cases}$$

$$R = 0.61\lambda/NA \qquad [4]$$

where R is the minimum value of r that makes the right side of Eq. 3 zero. The circular area with radius R is called the "point spread area" and it is represented by the symbol S. Equation 2 can then be

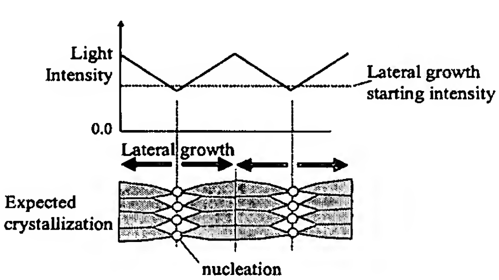

Figure 2. Target of light intensity distribution and expected crystallization.

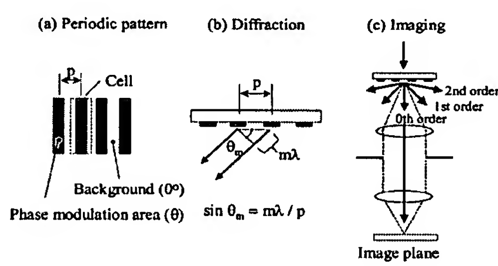

Figure 4. Control of light intensity by duty phase modulator: (a) periodic pattern model, (b) diffraction by duty phase modulator, and (c) imaging by duty phase modulator.

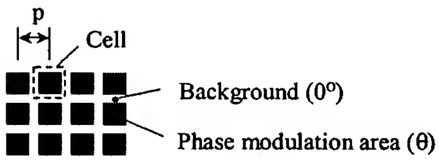

Figure 5. Two-dimensional cells.

simplified to an integral of the complex amplitude transmittance $T(\xi,\eta)$ in S, which has a center at (x,y). Because the phase modulator changes the phase of light but not its amplitude, the complex amplitude transmittance $T(\xi,\eta)$ can also be expressed as a function of the phase distribution $\varphi(\xi,\eta)$ in the same way as Eq. 1. Thus, a general equation that gives the amplitude due to a duty phase modulator is obtained

$$U(x,y) = \int_S e^{i\varphi(\xi-x,\eta-y)}d\xi d\eta \qquad [5]$$

This equation is similar to Eq. 1 described above. Equation 1 has the condition that the phase distribution pattern $\varphi(x)$ must be periodic. However, Eq. 5 has no restriction and $\varphi(\xi,\eta)$ may take a nonperiodic pattern.

As described later, when p is smaller than $R, U(x,y)$ does not locally depend on the position coordinates.

Novel Duty Phase Modulator

A more specific equation can be devised under the condition that the phase modulation is binary, that is, the phase values in the phase modulation area are of one kind. Here, we denote the phase value of the phase modulation area by θ and the duty by D and we set the phase value of the background to be 0° and its duty to be $1 - D$. In addition, we assume that there are enough cells within S. The percentage of the phase modulation area in the point spread area is approximately the same as D and it is not expected to depend upon the location of the center of the point spread area. As a result, Eq. 5 can be simplified. Hereafter, the functions containing position coordinates are abbreviated

$$U = D\,e^{i\theta} + (1 - D)e^{i0} \qquad [6]$$

Because the light intensity, I, is the square of the absolute value of the amplitude, U, the following equation is obtained

$$I = |U|^2 = (2 - 2\cos\theta)D^2 - (2 - 2\cos\theta)D + 1 \qquad [7]$$

Equation 7 gives the light intensity on the image plane when the phase modulation is binary. Figure 7 shows Eq. 7 graphically. The light intensity, I, becomes a minimum at a duty of 50%. This minimum can be arbitrarily set in the range 0–1 by changing θ, as

$$I_{\min} = (1 + \cos\theta)/2 \qquad [8]$$

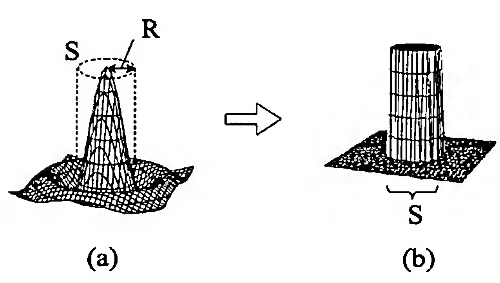

Figure 6. Approximation of amplitude point spread function: (a) amplitude point spread function expressed by Eq. 3 and (b) approximation to a cylindrical function.

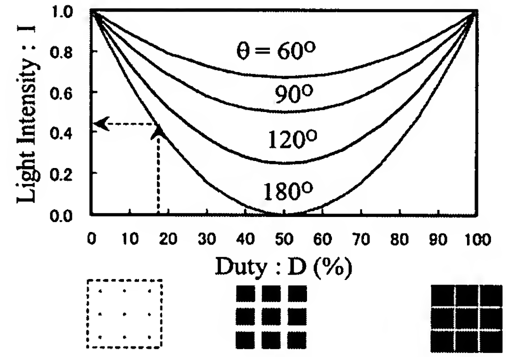

Figure 7. Relation between duty and light intensity.

Here p was assumed to be sufficiently small compared with R of the point spread area. When p is large, this approximation does not hold and the light intensity distribution is not uniform. Thus, an irregularity in the light intensity is expected to appear.

An optical simulation based on scalar diffraction theory was conducted to determine the necessary cell pitch that does not cause light intensity irregularity. The light intensity irregularity on the image plane was examined by changing the value of p with respect to R. A square-shaped phase modulation area with a phase value of 180° and duty 14.6% was used as a duty phase modulator. In this case, the light intensity is expected to be 0.5 from Eq. 7. In addition, an optical imaging system with wavelength 248 nm and numerical aperture 0.13 was assumed. In this case, R of the point spread area is 1.16 μm from Eq. 4. For the optical simulation, the lithography simulation software SOLID-C was used.

The distribution of the light intensity with respect to p/R is shown in Fig. 8a. When p/R is less than 1.2, the distribution is uniform. When p/R is more than 1.4, an irregularity in the light intensity appears. The distribution of the light intensity at $p/R = 1.6$ is shown in Fig. 8b. It was found that irregularity disappears completely when $p/R < 1$ for any case.

We want to form a light intensity distribution that changes within a plane using the duty phase modulator. It can be seen from Eq. 5 that the intensity is determined only by the pattern in the point spread area. Therefore, even when the duty changes within a plane, it is expected that Eq. 7 holds as long as the change is mild compared with the size of the point spread area.

In order to confirm this prediction, an accurate distribution of light intensity was determined by an optical simulation. We designed

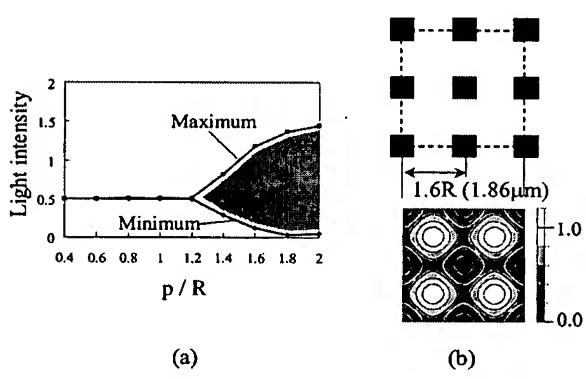

Figure 8. Influence of cell pitch on light intensity distribution: (a) maximum and minimum of the light intensity with respect to p/R and (b) distribution of the light intensity at $p/R = 1.6$.

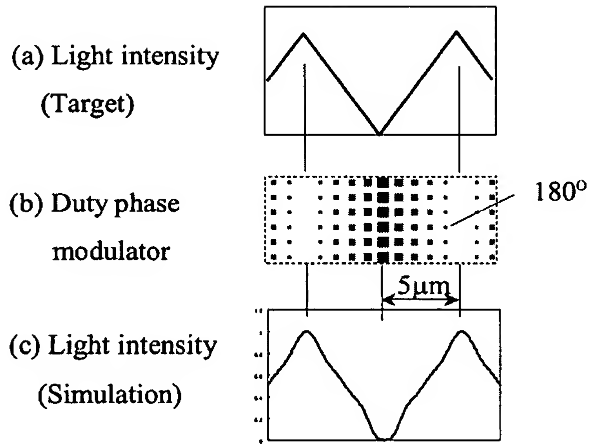

Figure 9. Light intensity by simulation: (a) light intensity target, (b) designed duty phase modulator, and (c) light intensity of the duty phase modulator by simulation.

a duty phase modulator based on Eq. 7 with the objective of obtaining a V-shaped distribution with a bottom intensity of zero. The cell pitch was set at 1.0 μm and the phase was set at 180°. The results of the optical simulation are shown in Fig. 9. An optical system with wavelength 248 nm, coherence factor 0.5, and numerical aperture 0.13 was assumed. The value of p/R was 0.86 in this case, which is in the range where intensity irregularity does not occur, as shown in Fig. 8.

As shown in Fig. 9c, the required distribution could be achieved. Thus, it is confirmed that Eq. 7 is a good design guideline even for the intensity distribution, which changes within a plane. This can also confirm the validity of the three approximations used: the approximation of a coherent imaging system, the approximation of the point spread function shown in Fig. 6, and the approximation used in the derivation of Eq. 5.

Experimental

A duty phase modulator was prepared and the distribution of the generated light intensity was measured.

A projection optical system with wavelength 248 nm, numerical aperture 0.13, and coherence factor 0.5 was used. Cells with a size equivalent to a 1-μm square on the image plane were adopted for the duty phase modulator. The phase modulation areas were arranged with duties of 0, 5, 11, 18, 28, and 50% in respective cells. The phase modulation areas were prepared on a quartz substrate by forming steps 244-nm deep, which corresponds to a phase difference of 180°.

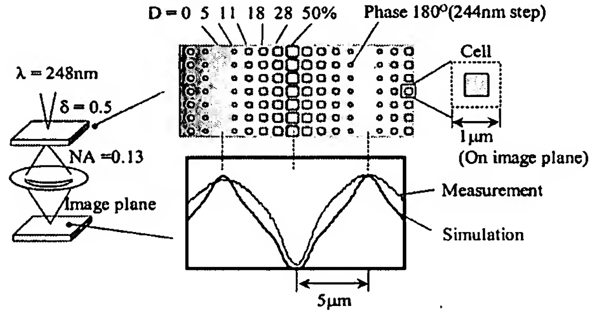

Figure 10. Measurement result of light intensity corresponding to the duty phase modulator.

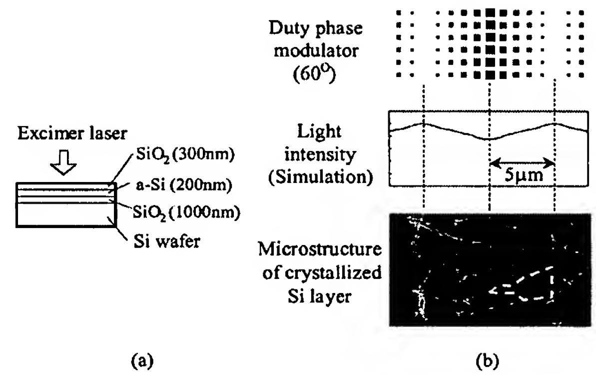

Figure 11. Crystallization of amorphous Si film: (a) layer structure and (b) microstructure of the crystallized Si layer corresponding to the duty phase modulator (SEM image after Secco etching).

An image of the prepared duty phase modulator observed with an optical microscope, the light intensity distribution predicted by the simulation, and the measured light intensity distribution are shown in Fig. 10. It was confirmed that the measurement and the simulation are in good agreement. In addition, it was confirmed that a V-shaped distribution could be achieved.

Subsequently, crystallization experiments were performed with the duty phase modulator. The conditions and results are shown in Fig. 11. A duty phase modulator was prepared with a phase 60° to set the bottom of the V-shaped distribution to the lateral growth starting intensity. Crystallization of amorphous Si film was conducted with the projection optical system shown in Fig. 10. As a result, 5-μm-long Si crystal grains with a high packing efficiency were successfully grown.

Discussion

As shown by the photo in Fig. 11, various crystalline grain shapes are produced, for example, triangular and rectangular grains. This crystallization pattern is different from the ideal pattern shown in Fig. 2 and is not desirable.

The cause of the irregularity of the grain shapes is thought to be as follows: At the first stage of the crystallization, many nuclei with different orientations are generated densely along an equi-intensity bottom line of the V-shaped light intensity distribution. At the second stage, lateral growth starts from each nucleus. In the process, "lucky" grains with preferential orientation can grow, inhibiting the growth of other grains. As a result, nonideal grain shapes are generated.

We expect that such irregularity of grain shapes can be suppressed by several methods. One possible method is to use a two-dimensional light-intensity distribution, which restricts lateral growth into a narrow region. Another method is to thin the Si film and use surface energy effects.[5]

Conclusions

A duty phase modulator was devised for advanced PMELA method. The principle, design method, and advantages of this duty phase modulator were described. This device can freely control the light intensity distribution and can be easily designed. A perfect V-shaped distribution was achieved and 5-μm-long Si crystal grains with a high packing efficiency were successfully grown using this modulator.

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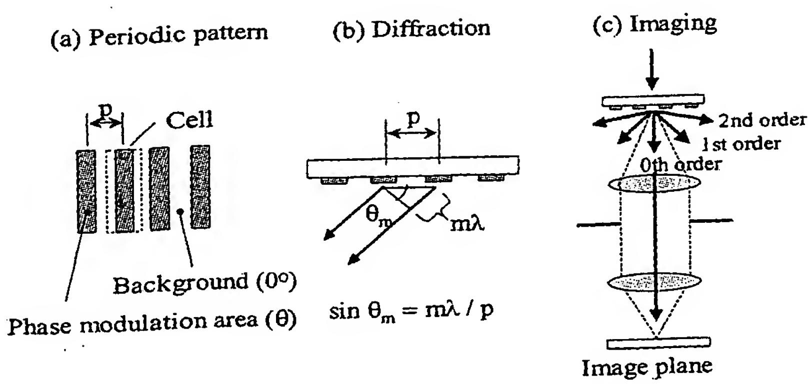
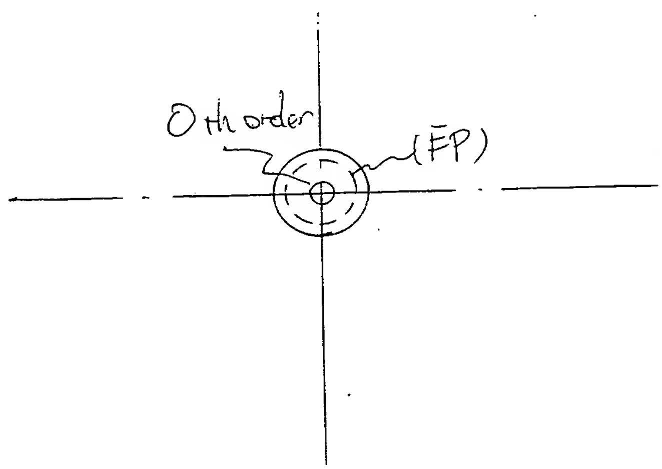

(a) Periodic pattern
p
Cell
Background (0°)
Phase modulation area (θ)
(b) Diffraction
p
θm
mλ
sin θm = mλ / p
(c) Imaging
2nd order
1st order
0th order
Image plane


0th order
(FP)